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STATIC UNIAXIAL STRAIN BEHAVIOR OF 15 ROCKS TO 30 KB

FINAL REPORT

W.F. BRACE

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Defense Atomic Support Agency

Washington, D.C. 20305

Department of Earth and Planetary Sciences

Massachusetts Institute of Technology

Cambridge, Massachusetts 02139

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ABSTRACT

Samples of 15 rocks with porosity ranging from nearly zero to 40 per cent were deformed in uniaxial strain to stresses which reached 31 kb. The principal stress ratio and the volumetric strain were recorded for comparison with experiments done statically elsewhere and with results from shock loading.

The stress-strain relations of low porosity rocks such as Westerly granite are nearly identical with those reported for shock loading. For material with porosity greater than about 2 per cent, permanent compaction occurred at the stresses imposed here. Compaction was apparently time-dependent, for nearly twice as much compaction was observed in our static experiments as in shock loading. Macroscopic faulting was not observed.

For rocks of low porosity the stress-strain relation in uniaxial strain loading is closely predictable from compressibility, suggesting that behavior of these rocks was elastic, or, at least, recoverable even to high stress levels. However, Poisson's ratio given by the stress ratio in uniaxial loading exceeds that directly measured statically by an appreciable amount, particularly for calcite marble.

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INTRODUCTION

In a state of uniaxial strain, two of the principal strains are zero. Strain is usually assumed to be uniaxial in material loaded by a plane shock wave; this type of loading is achieved in impact experiments [Jones and Froula, 1969], and approximately in underground nuclear explosions [Butkovich, 1965]. The unique strain direction is perpendicular to the shock front. In tectonically inactive regions of the Earth's crust where, for example, vertical compaction in flat-lying rocks is taking place, strain may also be uniaxial [Birch, 1955].

The mechanical behavior of rock loaded in uniaxial strain is poorly understood. Few experimental studies are available. How, for example, do rocks fail in uniaxial strain, and is behavior prior to failure elastic in the sense that it is predictable from independent measurement of elastic properties? What is the role of porosity? One might suspect that rocks of high porosity will respond to this type of loading quite differently from those of low porosity, particularly when stresses are compressive. Finally, what is the role of strain rate? Does rock under uniaxial strain behave the same at very high strain rates (shock loading) as it does at low strain rates (geologic loading)? The present study was designed to throw light on questions such as these. The experiments are termed "static" to emphasize the contrast in loading rate with experiments with uniaxial shock loading.

Previous Work

Serata [1961] investigated rock-salt, limestone, and dolomite under conditions approximating uniaxial strain. Cylindrical samples were compressed axially while being restrained laterally by thick-walled steel cylinders. The lateral strains were not zero in his experiments, but were quite small. Serata reported yielding in his materials, particularly in the rock-salt. Unfortunately, the materials he used have little application to the problem at hand, and there is some question as to the exact conditions of strain in his experiments. Hendron [1963] and Tsung [1966] tested a variety of sands at quite low pressures using a triaxial configuration in which lateral deformation of material was monitored. Confining pressure was varied so as to maintain zero lateral strain. Brown et al [1967] and Smith et al [1969] studied the behavior of everal rocks (granite, tuff, diabase, rhyolite, and concrete) in uniaxial strain, using Hendron's technique. They were capable of applying axial stress to 5 kb and confining pressure to 2 kb. The sample used was a very short cylinder. They reported a number of interesting characteristics of the elastic behavior of their materials, including maxima in the moduli at around a kilobar stress. No failure of their rocks was reported. The significance of porosity were not particularly clear, although they observed some densification of their more porous materials. Swanson [1970] loaded Westerly granite, Cedar City tonalite and a quartzitic sandstone (the Nugget sandstone of this study) in uniaxial strain as well as along other laoding paths. His main objective was development of constitutive relations for rocks, although he investigated several of the questions posed above. He reported, for example, that volume contraction during uniaxial strain of Westerly granite was closely predictable from compressibility. He found no evidence of failure in the granite for stress as high as 11 kb. His technique of loading and strain measurement were nearly identical to that used here, although he was limited to confining pressure of about 6 kb. Loading rate was similar to this study. No microscopic observations were given.

A number of rocks have been subjected to shock loading in order to determine an equation of state (see, for example, McQueen et al [1967]; Lombard [1961]; Ahrens and Gregson [1964]) or fracture or yield characteristics (for example, Petersen et al [1970]; Ahrens and Rosenberg [1968]; Giardini et al [1968]). There have been few attempts to correlate shock results with those uniaxial laboratory experiments which we will term static; strain rates in the former reach $10^7 sec^{-1}$, in the latter they range from 10^{-3} to $10^{-6} sec^{-1}$. One noteworthy study is that of Froula and Jones [1969] who studied Westerly granite, Solenhofen limestone, Cedar City tonalite, and Nevada Test Site tuff. Solenhofen limestone behaved linearly up to crushing at a stress of 6 kb; the crushing observed at higher stress was time-dependent. Westerly granite behaved elastically to the maximum stress of 45 kb applied during their experiment. Based on a reinterpretation of the granite data, Gregson, Isbell, and Green [1970] reported evidence of yield in the granite at a stress of about 17 kb.

The Present Investigation

We follow in essence the procedure of Brown et al., and Swanson, who used jacketed cylindrical samples of rock with strain gauges fixed to the surface to measure axial (ε_1) and circumferential (ε_3) strains. Pressure and axial stress were applied to the sample and varied independently in such a way that the lateral strain ε_3 was maintained at zero. The two stresses, σ_1 and σ_3, were observed during loading as well as the single strain ε_1, which equals volume change. Compression here is a positive stress; volumetric compaction is a negative strain.

A suite of rocks from our previous studies was chosen particularly for the problems at hand. Porosity ranged from 40 per cent to nearly zero; composition covered typical igneous rocks, schist, tuff, and sandstone. As many rocks as possible were included from previous shock studies.

We report here the stress-strain relations for these materials under uniaxial loading to stresses which reached about 30 kb, a limit set by our ability to generate a confining pressure and, therefore, a radial stress of 10 kb. For approximately half the suite of rocks, strains were nearly recoverable in our experiments, and for these compressibility was determined to 10 kb. This served two purposes; it provided a sensitive test of cracking by comparison of initial compressibility before and after loading, and it enabled us to compare volumetric strains in uniaxial and hydrostatic situations, as in the work of Swanson [1969]. Also for these rocks, static Poissons ratio was measured as a function of pressure. This provided a comparison with the value obtained from the relation between σ_1 and σ_3 during uniaxial loading.

Only macroscopic observations are given here. Microscopic investigation of the material is still in progress and will be reported later.

THE ROCKS STUDIED

Total porosity and modal analysis of the rocks studied are listed in Table 1. Most of the rocks have been investigated before in our studies of elastic and electrical properties as indicated. The Cedar City tonalite was supplied by S. Blouin of Kirtland Air Force Base. It is from the same general area as material used by Jones and Froula, [1969], Green and Perkins [1969], and Swanson, [1970]. A detailed petrographic description is given in Green and Perkins, [1969]. Our specimens of Westerly granite and Solenhofen limestone are from different blocks as those of Swanson and Jones and Froula. The Navajo sandstone is from an unknown location. The Nugget sandstone (quartzitic sandstone of Swanson) comes from Parleys Canyon, Salt Lake County, Utah. The schist was supplied by Dr. Larry Schindler, OCE, from an undisclosed site. The Barre granite is from material currently being quarried at Barre, Vermont. Porosity was determined by immersion [Brace, Orange, and Madden, 1965], and for the new materials here has an uncertainty of 0.002.

TABLE I: Rocks studied

Rock	Porosity %	Modal analysis	Reference
Diabase, II Frederick, Md.	0.1	49 an_{45}, 46 pyr, 3 ox, 2 mica	<u>Brace</u> <u>and</u> <u>Orange</u>, 1968
Gabbro San Marcos, Cal.	0.2	70 an_{42}, 12 mica, 8 pyr, 7 am, 3 ox	<u>Brace</u> <u>and</u> <u>Orange</u>, 1968
Schist source unknown	0.3	40 qu, 26 mica, 15 or, 7 an_5, 7 gar, 5 ox	-----
White marble source unknown	0.3	99 ca	<u>Brace</u> <u>and</u> <u>Orange</u>, 1968
Lynn felsite Saugus, Mass.	0.3	40 or, 35 an_{30}, 25 qu, 2 ox, 1 mica	<u>Brace</u> <u>and</u> <u>Orange</u>, 1968
Limestone II Oak Hall, Pa.	0.6	98 ca-do, 1 qu, 1 ox	<u>Brace</u> <u>and</u> <u>Orange</u>, 1968
Granite Barre, Vt.	0.6	26 qu, 25 or, 37 an_{10}, 12 mica	<u>Nur</u> <u>and</u> <u>Simmons</u>, 1970

TABLE I (con't)

Granite Westerly, R. I.	0.9	27.5 qu, 35.4 mi, 31.4 an_{17}, 4.9 mica	Brace, Orange, Madden, 1965
Nugget sandstone Utah	1.9	99 qu	Swanson, 1970
Pottsville sandstone Tennessee	2.9	46 qu, 41 or, 11 mica, 2 ox	Brace and Orange, 1968
Limestone Solenhofen	4.8	99 ca	Brace, Orange, Madden, 1965
Tonalite Cedar City, Utah	7	55 an_{20-50}, 20 qu, 8 pyr, 5 mica, 2 ox	Perkins and Green, 1969
Limestone Bedford, Ind.	12	99 ca	Brace and Orange, 1968
Navajo sandstone source unknown	15.5	99 qu, 1 ox	----
Rhyolite Tuff Colorado	40	33 gl, 20 qu, 40 or, 4 an_{10}, 2 ox	Brace and Orange, 1968

TABLE I (con't)

ABBREVIATIONS

qu	quartz	mica	mica, clay
or	orthoclase	gl	glass
ca	calcite	gar	garnet
do	dolomite	ox	oxides
pyr	pyroxene	mi	microcline
an	plagioclase		

EXPERIMENTAL PROCEDURE

Jacket The function of the jacket was twofold, to exclude the hydrostatic pressure medium from the rock sample, and to provide a smooth continuous surface for mounting strain gauges. Inasmuch as circumferential strains were to be maintained equal to zero during the experiments, strain in the jacket would also be negligible, so that strength of jacket did not have to be considered. Seamless tubing 1.85 cm ID and 0.033 cm wall thickness of annealed copper was used; spun caps of copper were soft soldered to the tubing.

Sample preparation Precisely ground right circular cylinders were prepared from rock cores. Diameter was 1.85 cm, length 3.8 cm. At this stage porosity was determined. Then, the rocks of low porosity were jacketed as described above. The porous materials (porosity greater than a few percent) were given special treatment prior to jacketing.

Previous work had shown that porous rocks such as the tonalite or the Indiana limestone cannot be jacketed and gauged in the usual manner. Under high pressure the jacket is forced into surface pores; failure of the jacket often occurs. Even without this, the apparent strain reported by the gauges is often very different from the true strain in the interior of the rock. To prevent collapse of jacket and gauges into surface pores, a filled epoxy was applied to the surface of the rock prior to jacketing. Various epoxies were used. The filler was metal powder so chosen that the elastic properties of the cured epoxy approaches that of the rock forming minerals. In a previous unpublished study of the tonalite, this procedure prevented surface pore collapse under pressure; strains recorded from measurements at the curve of samples treated in this manner agreed with those measured externally.

Before strain gauges were mounted, the jacketed samples were subjected to several hundred bars confining pressure. This seated the jackets firmly against the surface of the samples and also revealed jacket leaks. If dimples and other depressions appeared at this stage in the jacketed surface, they were filled with solder and smoothed with a hand grinder.

Strain measurement Strain gauges were BLH epoxy-backed foil types (FAE-50-12S6 or FAE-100-12S6) cemented with EPY-150 cement cured according to manufacturers specification, using the additional precautions outlined in Brace [1965]. They were mounted axially and circumferentially on the samples.

The effect of pressure on strain gauges was taken into account following Brace [1964]. The pressure effect for the present gauges was $+0.60 \times 10^{-7}$ bar^{-1}. The apparent strain in the axial direction, ε_1, was corrected for the pressure effect in the usual way; the corrected quantity is given in Table 2.

The circumferential strain was to be maintained equal to zero. Because of the pressure effect on the gauge, this required that the gauge indicate an apparent strain exactly equal to the pressure effect. The experiments were so conducted that this condition was satisfied.

<u>Loading procedure</u> The gauged samples were pressurized (medium was petroleum ether) and loaded in a large screw-driven press. Pressure was generated externally, and recorded together with total axial force exerted by the press and the two strains as described above. Procedure was somewhat different for low and high porosity rocks. For the latter, application of pressure or axial compression generally caused permanent compressive strain, whereas for the former, strains were typically recoverable. For the low porosity rocks only, compressibility was determined before and after uniaxial strain loading. As noted above, the purpose was to detect possible cracking during uniaxial strain loading. A pressure of about 1 kb was applied for two or three cycles.

During an actual experiment, procedure was as follows. The sample was placed inside the pressure vessel and leads were connected to the strain gauges. The motor driven screw was then advanced at a rate equivalent to a strain of about 10^{-5} sec^{-1}. A continuous record to axial force <u>vs</u> confining pressure was made, as well as a record of pressure vs both strains. As soon as the axial piston contacted the sample, load began to increase; pressure was then manually raised so as to maintain the circumferential strain equal to zero. As the piston advanced, continuous plots were made until the fluid pressure reached 10 kb, which was the limit of our pumping system. Axial load and then pressure were dropped, and in the case of the low porosity samples, compressibility to 1 kb remeasured. For the high porosity rocks, final external dimensions were measured with a micrometer.

Axial load was measured with an external force cell which had been calibrated against a proving ring. Accuracy of force measurement was about 1 percent. A correction for O-ring friction at the pressure vessel seals was applied to the measured force during data reduction.

Pressure was measured by a manganin coil which also, through a bridge, provided an electrical signal suitable for recording. Accuracy was about 0.5 percent.

Strains were accurate to no better than 1 percent, the uncertainty in the gauge factor. The condition of no circumferential strain could be maintained to about $\pm 25 \times 10^{-6}$. It is not known how strain gauge characteristics change for strains as large as those recorded for the more porous samples (up to 17 percent). Considerable uncertainty, perhaps as high as 5 or 10 percent, must be attached to the values of ε_1 given below which exceed a few percent.

The data are collected in Table 2 for the fifteen rocks. Duplicate samples of Westerly granite were run to test reproducibility so that two sets of data appear for that entry in Table 2.

Compressibility Measurement of linear strain as a function of hydrostatic pressure was carried out for the low porosity rocks for two reasons. First, increase in crack porosity during uniaxial strain loading could be estimated using the procedure outlined in Brace [1965]. Second, change in volume as a function of pressure could be compared with volume changes during uniaxial loading. In Table 2 the nonrecoverable strain, or new crack porosity, remaining after one cycle of uniaxial strain loading is given as η_p. This is given for the calcite rocks (marble and limestones) even though it was likely that plastic flow has occurred; this is known [Paterson, 1963] to cause anamalous length changes upon release of pressure that may have nothing to do with cracks.

Volume compressions to 10 kb for the low porosity rocks are listed in Table 3. Volumetric compressions have been assumed to be three times the measured linear compressions

TABLE II Stresses, Strains and Porosity Change During Uniaxial Strain Loading

Stresses are in kilobars, strains in 10^{-4}

Compressive stress is positive, compressive strain negative

	Radial stress, σ_3											
	0	0.5	1	2	3	4	5	6	7	8	9	10
Diabase												
σ_1		1.83	3.34	6.0	8.6	11.0	13.3	15.5	17.3	19.0	21.0	23.0
$-\epsilon_1$		12.0	22.8	45.0	63	82.0	99	116	132	149	164	181
η_p	<0.5											
Gabbro												
σ_1		1.58	2.76	5.39	7.74	9.82	11.9	14.0	15.9	17.8	19.7	21.6
$-\epsilon_1$		16.5	31.1	58.0	84.2	108	132	155	179	200	221	243
η_p	<0.5											
Schist												
σ_1		1.78	2.86	4.98	6.76	8.30	10.3	12.0	13.7	15.3	17.0	18.6
$-\epsilon_1$		29.0	42.1	72.4	99.4	124	149	170	193	215	237	258
η_p	+3.6											
White Marble												
σ_1		1.28	2.02	3.48	4.83	6.03	7.17	8.32	9.41	10.5	11.6	12.6
$-\epsilon_1$		19.0	29.8	50.0	68.8	86	103	119	134	149	164	180
η_p	+60											
Felsite												
σ_1		1.50	2.90	5.60	8.2	10.6	12.7	14.8	16.9	19.0	20.9	22.8
$-\epsilon_1$		27.2	31.5	57.0	82.0	105	127	150	171	194	216	237
η_p	+1.0											

TABLE II (Cont.)

		Oak Hall Limestone										
σ_1		1.35	2.63	4.74	6.69	8.40	10.0	11.3	12.4	13.8	14.9	16.0
$-\varepsilon_1$		14.5	26.6	48.7	70.0	89.2	107	122	136	150	164	177
η_p	>+50											
		Barre Granite										
σ_1		2.19	3.71	5.96	8.55	10.8	12.9	14.9	16.8	18.7	20.5	22.3
$-\varepsilon_1$		32.4	49.6	82.4	111	138	165	189	212	236	257	277
η_p	∿3											
		Westerly Granite										
σ_1		1.96	3.37	5.77	8.50	10.9	13.2	15.5	17.6	19.8	22.0	24.1
		--	3.16	6.00	8.51	11.0	13.2	15.4	17.6	19.7	21.7	--
$-\varepsilon_1$		26.6	45.2	76.2	107	136	165	192	219	246	271	298
		--	42.8	77.9	110	141	171	198	226	253	279	306
η_p	+3.0											
	+4.2											
		Nugget Sandstone										
σ_1		3.14	4.86	8.40	11.6	14.4	17.3	20.1	22.6	24.9	26.8	28.5
$-\varepsilon_1$		62.0	103	168	225	276	325	371	412	450	483	516
η_p	<0.5											
		Pottsville Sandstone										
σ_1		2.56	4.72	8.67	12.1	15.6	18.4	21.2	23.9	26.1	28.6	30.9
$-\varepsilon_1$		61.0	100	175	237	301	343	393	439	471	523	566
η_p	∿-260											

TABLE II (Cont.)

						Solenhofen Limestone						
σ_1		1.28	2.32	4.54	5.84	6.89	7.82	8.71	9.68	10.7	11.7	12.7
$-\varepsilon_1$		13.3	28.2	56.5	84.8	118	158	217	267	323	388	457
η_p	$\sim$-230											
						Tonalite						
σ_1		2.26	3.71	6.30	8.60	10.7	12.9	14.8	16.8	18.7	20.5	22.4
$-\varepsilon_1$		107	171	251	324	386	440	493	541	587	627	668
η_p	-420											
						Bedford Limestone						
σ_1		1.45	2.02	3.32	4.69	6.00	7.27	8.57	9.71	11.0	12.1	13.4
$-\varepsilon_1$		93.0	175	448	675	855	979	1070	1170	1250	1310	1360
η_p	-980											
						Navajo Sandstone						
σ_1		1.80	3.22	5.26	6.75	8.34	10.1	11.7	13.5	15.2	17.0	19.0
$-\varepsilon_1$		62	134	285	454	590	725	850	955	1050	1140	1210
η_p	$\sim$-910											
						Rhyolite Tuff						
σ_1		1.58	2.39	3.79	5.54	7.35	9.23	11.2	13.0	14.8	16.6	18.3
$-\varepsilon_1$		115	217	546	746	940	1170	1360	1480	1530	1650	1760
η_p	-1310											

TABLE III Volume Compressions
Units are 10^{-4}

Rock	Pressure, kb								
	0.6	1.2	2.4	3.6	4.8	6.0	7.2	8.4	9.6
Diabase	8.8	17.3	33.6	49.2	64.6	79.7	94.4	109	124
Gabbro	17.5	41.7	55.0	76.5	97.2	117	137	156	175
Schist	24.5	40.7	68.4	95.1	120	144	168	188	210
Marble	20.1	32.8	51.9	69.5	86.8	104	120	137	153
Barre Granite	26.3	42.8	69.4	93.2	116	137	157	177	198
Westerly Granite	19.9	35.0	62.5	88.0	113	137	161	184	207
Solenhofen	13.1	26.2	52.5	--	--	--	--	--	--

in the axial direction. Where the rock is relatively isotropic this will be close to the actual volume compression; where the rock is anisotropic, it will not be, but it is probably the most appropriate quantity to compare with ε_1 from the uniaxial strain experiment.

Static Poisson's ratio Samples of certain of the low porosity rocks were set up just as for the uniaxial strain experiment. An axial load of several kilobars was applied at a number of different confining pressures starting at about 1 kb. Both axial and circumferential strains were observed and their ratio measured. This enabled Poisson's ratio to be determined as a function of pressure to 10 kb. The values, listed in Table 4, have an uncertainty of about 10 percent. Data from two different samples of Westerly granite are given.

TABLE IV Poisson's Ratio

Rock	Pressure, kb							
	1.2	2.4	3.6	4.8	6.0	7.2	8.4	9.6
Diabase	0.29	0.29	0.29	0.30	0.29	0.29	0.31	0.30
Gabbro	0.26	0.26	0.26	0.26	0.27	0.27	0.28	--
Marble	0.20	0.29	0.29	0.30	0.30	0.31	0.29	0.30
Barre Granite	0.27	0.24	0.24	0.25	0.26	0.26	0.24	0.26
Westerly Granite	0.22	0.23	0.23	0.24	0.24	0.25	0.25	0.25
	0.21	0.22	0.22	0.22	0.23	0.23	0.23	0.23

DISCUSSION

Reproducibility Results for Westerly granite are plotted in Figure 1 as σ_1 vs σ_3 and σ_1 vs ε_1. The two samples studies here were vitually identical in the σ_1-σ_3 plot (see also Table 2) and very close to that of Swanson [1969] whose values are also shown in Figure 1. In the $\sigma_1 - \varepsilon_1$ plot, our two samples differed by about two percent and were within a few percent of the Swanson values. Data from two different shock experiments are also given in Figure 1 for comparison with our static values. The differences, which are seen to be small, are discussed below. One of the shock studies was done on the so-called Bradford granite [Grine, 1970] which is said to come from a quarry adjacent to that of Westerly granite.

Agreement for the tonalite (Figure 2) is seen to be less satisfactory than for Westerly granite. Our $\sigma_1 - \sigma_3$ values differ from those of Swanson by about 5 percent; our ε_1 values are about twice as high.

Agreement in $\sigma_1 - \sigma_3$ for granite and tonalite is probably as good as can be expected for two different laboratories, particularly when the samples are not taken from the same block of rock. The agreement in the $\sigma_1 - \varepsilon_1$ for Westerly is also quite satisfactory. The very poor agreement in the $\sigma_1 - \varepsilon_1$ values for the tonalite may be due to differences in the samples or simply to experimental errors. Clearly, this requires further study.

Recoverable behavior Recovery as opposed to yield is defined in terms of η_p. A sample is said to recover if, after an excursion in uniaxial strain loading, η_p is less than about o.5 x 10^{-4}. Much smaller strains than this can be detected when strain gauges are used in more conventional applications, but in view of the large strains imposed here this is quite a satisfactory limit.

η_p (Table 2) is small and typically positive (denoting a permanent increase in volume) for all the rocks through Nugget sandstone; for the more porous rocks making up the balance of the Table, η_p ranges up to -13.1 percent. Behavior of the first group, which recovered, is discussed here; that of the second, in which permanent volumetric compaction took place, is considered below.

The small positive strains shown by many of the rocks may be a manifestation of the effect first noted by Paterson [1963] and, more recently studied in detail by Edmond [1969]. They noted that a wide variety of ductile rocks (limestone, marble, soapstone, polycrystalline alkali halides and talc, and serpentinites) increased in volume permanently during the release of pressure following triaxial deformation to large permanent axial strains. The volume increase was particularly marked for the calcite rocks. It is of interest that in our study marble and Oak Hall limestone increased in volume 50 to 60 x 10^{-4}. This might imply, according to <u>Paterson</u>, that some plastic deformation of these materials took place during uniaxial strain. A small increase in volume for schist, felsite and both granites was also noted (Table 2), although plastic flow of these materials in our experiments seems unlikely.

The volumetric strain, ϵ_1, for all of our rocks are compared as a function of σ_1 in Figure 3. The curves for the rocks which recovered are seen to be very nearly linear. With the exception of Pottsville and Nugget sandstones, all of the others are strongly curved. The marked linearity and small permanent strains of the low porosity rocks suggests that the recoverable behavior is largely elastic, and as such ought to be predictable from, say, compressibility. It can be readily shown that if behavior of an isotropic material during a uniaxial strain is purely elastic, then $\bar{\sigma}/\epsilon_1$ should equal P/θ, where $\bar{\sigma}$ is the mean stress, $(\sigma_1+\sigma_2+\sigma_3)/3$, and P and θ are pressure and volumetric strain respectively. In Figure 4, $\bar{\sigma}$ and ϵ_1 from uniaxial strain experiments

(Table 2) are compared with P and θ from hydrostatic compressions (Table 3). The agreement for the 6 rocks shown is seen to be good, even for the marble and schist, which are somewhat anisotropic. Even the initial curvature in the P - θ relation is followed rather closely, although this is a reflection of crack closure and, therefore, not an intrinsic elastic characteristic. The curves for the two granites are nearly identical; they should be inasmuch as their mineralogy is similar (Table 1). Many of the other similarities and differences in these curves are reasonable in terms of compressibility of the minerals making up the rocks.

Based on the above we conclude that the stress-strain behavior of the rocks with porosity up to about 2 percent during uniaxial strain is elastic, in the sense that it is predictable from compressibility. With more porous rocks volumetric compaction is superimposed on elastic behavior.

Poisson's ratio An independent test of elastic behavior is given by Poisson's ratio, ν, obtained, on the one hand, by direct measurement as a function of confining pressure and, on the other, from the elastic relation presumed to hold during uniaxial strain, namely, that

$$\sigma_3 = \nu\sigma_1/(1-\nu) \tag{1}$$

Comparison is made in Figures 5 and 6. The squares are obtained by applying (1) to the data given in Table 2. The circles give ν by direct measurement, from Table 4. The triangles for Westerly granite and diabase give additional direct measurements we have made on other samples in unpublished studies. In the plot for Westerly granite, results for two samples are given; the single set of crosses reflects the nearly identical stresses in both experiments.

In every case except the diabase, ν for uniaxial strain is significantly larger than ν from direct measurement. Values for the diabase should be remeasured. For the others, differences are too large to be explained either by experimental error (note the differences in two samples for Westerly) or by anisotropy (above a few kb pressure elastic anisotropy of all but marble is very small). It is uncertain whether one should plot uniaxial ν against σ_1, or against σ_3 as has been done here. For the former, agreement is improved for the two granites and the gabbro; for the marble, the two values of ν still differ markedly.

Based on ν it would appear that, in contradiction to our previous conclusion, behavior of these rocks, although recoverable, may not be purely elastic. Perhaps plastic flow of calcite, in the case of the marble, or motion on closed cracks for the silicate rocks is significant. The latter is known to influence apparent elastic behavior in confined compression [Walsh, 1965] and may be significant here. For the marble, microscopic observations are needed to establish if calcite has flowed plastically; if not, then the effect may be due to sliding on cracks, combined perhaps with differences due to anisotropy.

From the differences shown in Figures 5 and 6, clearly one must be cautious in the use of Poisson's ratio in the analysis of uniaxial strain. The σ_1-σ_3 relation is often calculated for shock experiments through (1) using laboratory values of ν comparable to those obtained statically here (Table 4). Based on our comparison, an uncertainty in ν of 10 to 25 per cent would not be unusual; this would lead to even larger errors in the ratio σ_3/σ_1.

Permanent strain Appreciable permanent or nonrecoverable strain, η_p, was observed for all of the rocks having porosity greater than about 2 per cent. This took the form of an apparently homogeneous one-dimensional compaction. No faults or offsets of any sort were observed, although such features may be revealed under the microscope.

The magnitude of the permanent strain, η_p, correlates fairly well with initial porosity (Figure 7). The 45° line in this figure represents the maximum value of η_p. Pottsville sandstone and Bedford limestone are apparently quite close to this limit; the others are within about 40 per cent of complete compaction. It is interesting that the degree of compaction does not improve with the rocks which have the lowest strength, as might be expected. Probably a great many factors affect the degree of compaction at any given pressure, including grain size, shape of the pores, mineralogy, degree of alteration, and abundance and continuity of cracks.

In Figure 3 the shapes of the σ_1 - ϵ_1 curves for the high porosity rocks may be compared. The curves are of two types, those initially concave upward (Pottsville sandstone and tonalite) and those initially concave downward. This difference is probably due to differences in crack porosity; from electrical studies [Brace and Orange, 1968] rhyolite, Bedford limestone and Solenhofen limestones have little or no crack porosity, whereas Pottsville sandstone does.

The stress at which total compaction occurs can be roughly estimated from Figure 3. The dotted lines give curves which should be followed for the different rocks if porosity were zero. The stress at which the measured curves intersect these dotted lines would be the stress at which porosity reaches zero. For the two limestones, this stress appears to be 15 to 20 kb. For the Navajo sandstone this stress probably exceeds 30 kb. For the tonalite it may be a great deal higher.

For the rocks such as Solenhofen limestone, the shape of the $\sigma_1 - \varepsilon_1$ curve suggests that behavior was elastic up to the stress at which collapse of pores began. This can be tested in a plot of $\bar{\sigma}$ vs ε_1 by comparison with marble, which also consists only of calcite. We showed above that behavior of marble at all stresses was predictable from its compressibility (Figure 4). In Figure 8, $\bar{\sigma} - \varepsilon_1$ plots of marble and Solenhofen are compared, using data from Table 2. It is seen that the initial linear part of the Solenhofen curve is very nearly paralled with the curve for marble; the initial part of the marble curve is not linear because of crack closure in that material [Brace, 1965]. Thus, we conclude that behavior of Solenhofen limestone is elastic up to the stress at which permanent pore closure commences.

From the shape of the curves in Figure 3, tonalite, rhyolite and Bedford limestone may also have been initially elastic, but the stress at which pore closure began was apparently very low; data were not recorded at very low stresses, so that this cannot be definitely established. Finally, it is also of interest that for the two high porosity limestones, the stress at which pore collapse began seems to correlate with the degree of compaction (compare Figs. 3 and 7), as might be anticipated.

Comparison of shock and static behavior Uniaxial strain behavior in static and shock conditions can be compared for Westerly granite (Figure 1), tonalite (Figure 2) and Solenhofen limestone (Figure 8). Apparently there is no difference between static and shock conditions during, as we have termed it, recoverable behavior, for the granite at all stresses, and for the limestone, up to a mean stress of 5 kb. Beyond that, however, the difference is striking. There is nearly twice as much compaction of the tonalite and limestone under static as under shock loading. Compaction requires some small scale cracking so that this difference could be explained [Jones and Froula, 1969] if the cracking were time dependent. Fracture of brittle geologic materials is somewhat time dependent (see for example, Scholz, 1968); compressive strength of rocks decreases the order of 10 per cent per 10^3 decrease in strain rate [Brace and Martin, 1968]. The difference between the static and shock stress to produce a given strain, ε_1, is seen from Figure 2 and 8 to be about 30 per cent. This is roughly consistent with the difference in strain rates of about a factor of 10^{11}.

<u>Fracture and yield</u>. Complete discussion of fracture and yield in our materials must await microscopic examination of thin section. However, several observations can be noted here.

As discussed above, there was no macroscopic faulting or visible offsets in any of our samples after deformation. The large permanent strains in the porous rocks, of course, require small scale fracture or flow. In the low porosity rocks, such as Westerly granite, permanent strains were negligible, and on that basis we suspect that even small scale fracture or yield of these rocks is also negligible.

REFERENCES

Ahrens, T. J., and Gregson, Jr., V. G., "Shock Compression of Crustal Rocks; Data for Quartz Calcite and Plagioclase Rocks", J. of Geophysical Research, Vol. 69, No. 22, pp. 4839-4874, November 15, 1964.

Ahrens, T. J., and Rosenberg, J. N., "Shock Metamorphism; Experiments on Quartz and Plagioclase", in Shock Metamorphism of Natural Materials, ed. by French, B. M., and Short, N. M., Mono Book Corporation, Baltimore, Maryland, 1968.

Birch, F., "Physics of the Crust", Geol. Soc. America Special Paper 62, pp. 101-118, 1955.

Brace, W. F., "Effect of Pressure on Electric-Resistance Strain Gages", Experimental Mechanics, Vol. 4, No. 7, pp. 212-216, 1964.

Brace, W. F., "Some New Measurements of Linear Compressibility of Rocks", J. of Geophysical Research, Vol. 70, No. 2, pp. 391-398, 1965.

Brace, W. F., and R. J. Martin, III, "A Test of the Law of Effective Stress for Crystalline Rocks of Low Porosity", Int. J. Rock Mech. Min. Science, Vol 5, pp. 415-426, 1968.

Brace, W. F., and A. S. Orange, "Further Studies of the Effect of Pressure on Electrical Resistivity of Rocks", J. of Geophysical Research, Vol. 73, pp. 5407-5420, August 15, 1968.

Brace, W. F., Orange, A. S., Madden, T. M., "The Effect of Pressure on the Electrical Resistivity of Water-Saturated Crystalline Rocks", J. Geophysical Research, Vol. 70, pp. 5669-5678, 1965.

Brown, Wayne S., K. Lawrence De Vries, and James L. Smith, "Properties of Rocks Tested in One-Dimensional Compression", Tech. Rept. No. AFWL-TR-66-124, Univ. of Utah, Jan., 1967.

Edmond, J. M., "Effects of Pressure During Rock Deformation", Ph. D. Thesis, Australian National University, 1969.

Giardini, A. A., Lakner, J. F., Stephens, D. R., and Stromberg, H. D., "Triaxial Compression Data on Nuclear Explosion Shocked, Mechanically Shocked, and Normal Granodiorite from the Nevada Test Site", J. of Geophysical Research, Vol. 73, No. 4, pp. 1305-1320, February, 1968.

Gregson, V. G., Jr., Isbell, W. M., and Green, S. J., "Yield of Westerly Granite Under Shock Loading", Transactions, Amer. Geophys. Union, Vol. 51, No. 4, p. 423, April, 1970.

Grine, D. R., "Progress Letter No. 7, SRI Project PGU 7852 Stanford Research Institute, Menlo Park, California, 1970.

Hendron, A. J., "The Behavior of Sand in One-Dimensional Compression", RTD-TDR-63-3089, AFWL, Kirtland Air Force Base, New Mexico.

Jones, A. H., and Froula, N. H., "Uniaxial Strain Behavior of Four Geological Materials to 50 Kilobars", DASA-2209, March, 1969.

Lombard, D. B., "The Hugoniot Equation of State of Rocks", University of California, LRL-UCRL-6311, G-3294, February, 1961.

McQueen, R. G., Marsh, S. P., and Fritz, J. N., "Hugoniot Equation of State of Twelve Rocks", J. of Geophysical Research, Vol. 72, No. 20, pp. 4999-5036, October, 1967.

Nur, Amos, and Simmons, Gene, "The Effect of Viscosity of a Fluid Phase on Velocity in Low Porosity Rocks", Earth and Planetary Science Letters, 7, pp. 99-108, 1969.

Paterson, M. S., "Secondary Changes of Length with Pressure in Experimentally Deformed Rocks", Proc. Roy. Soc. London, A, Vol. 271, pp. 57-87, 1963.

Perkins, R. D., and Green, S. J., "Uniaxial Stress Behavior of Porphyritic Tonalite at Strain Rates to 10^3 Second", DASA-2200, February, 1969.

Petersen, C. R., Murri, W. J., and Cowperthwaite, M., "Hugoniot and Release-Adiabat Measurements for Selected Geologic Materials", J. of Geophysical Research, Vol. 75, No. 11, pp. 2063-2072, April, 1970.

Scholz, C. H., "Microfracturing and Inelastic Deformation of Rock in Compression," J. Geophysical Research, Vol. 73, pp. 1417-1432, 1968.

Serata, Shosei, "Transition from Elastic to Plastic States of Rocks Under Triaxial Compression", 4th Symposium on Rock Mechanics, Bull. of Min. Indus. Exper. Station, Penn. State University, pp. 73-82, 1961.

Smith, J. L., K. L. De Vries, D. J. Bushnell, and W. S. Brown, "Fracture Data and Stress-Strain Behavior of Rocks in Triaxial Compression", Experimental Mechanics, Vol. 9, pp. 348-355, 1969.

Swanson, S. R., "Development of Constitutive Relations for Rocks", Ph. D. Thesis, University of Utah, Utah, 1969.

Tzung, Fu-Kong, "Sand in One-Dimensional Compression", unpublished MS Thesis, University of Utah, June, 1966.

Walsh, J. B., "The Effect of Cracks on the Uniaxial Elastic Compression of Rocks", J. of Geophysical Research, Vol. 70, pp. 399-411, 1965.

FIGURE CAPTIONS

Figure 1 Uniaxial strain behavior of Westerly granite. The open circles and triangles are static experiments, the closed squares for shock loading. Grine's data pertain to Bradford granite.

Figure 2 Uniaxial strain behavior for Cedar City tonalite. Symbols as in Figure 1.

Figure 3 Stress-volumetric strain. Curves are identified by the abbreviated rock name. The small number on some of the curves is porosity in per cent. The dotted lines are explained in text.

Figure 4 Comparison of uniaxial strain with hydrostatic compression for low porosity rocks. The curves are shifted vertically for clarity. The curves give pressure, P, vs volumetric strain θ for hydrostatic compression. The circles give $\bar{\sigma}$ vs ε_1 for uniaxial strain loading.

Figure 5 Comparison of Poisson's ratio for uniaxial strain loading with the value measured directly. Squares are uniaxial strain conditions, and circles and triangles are by direct measurement. Data for two samples of granite are shown.

FIGURE CAPTIONS (con't)

Figure 6. Comparison of Poisson's ratio for uniaxial strain loading with the value measured directly. Squares are uniaxial strain conditions, and circles are by direct measurement.

Figure 7. Comparison of permanent volumetric compaction with initial porosity for high porosity rocks. Rock names are abbreviated. Size of boxes indicates uncertainty.

Figure 8. Mean stress _vs_ strain for marble and Solenhofen limestone. The static Solenhofen data are from this study, the shock data from _Jones and Froula_, [1969].

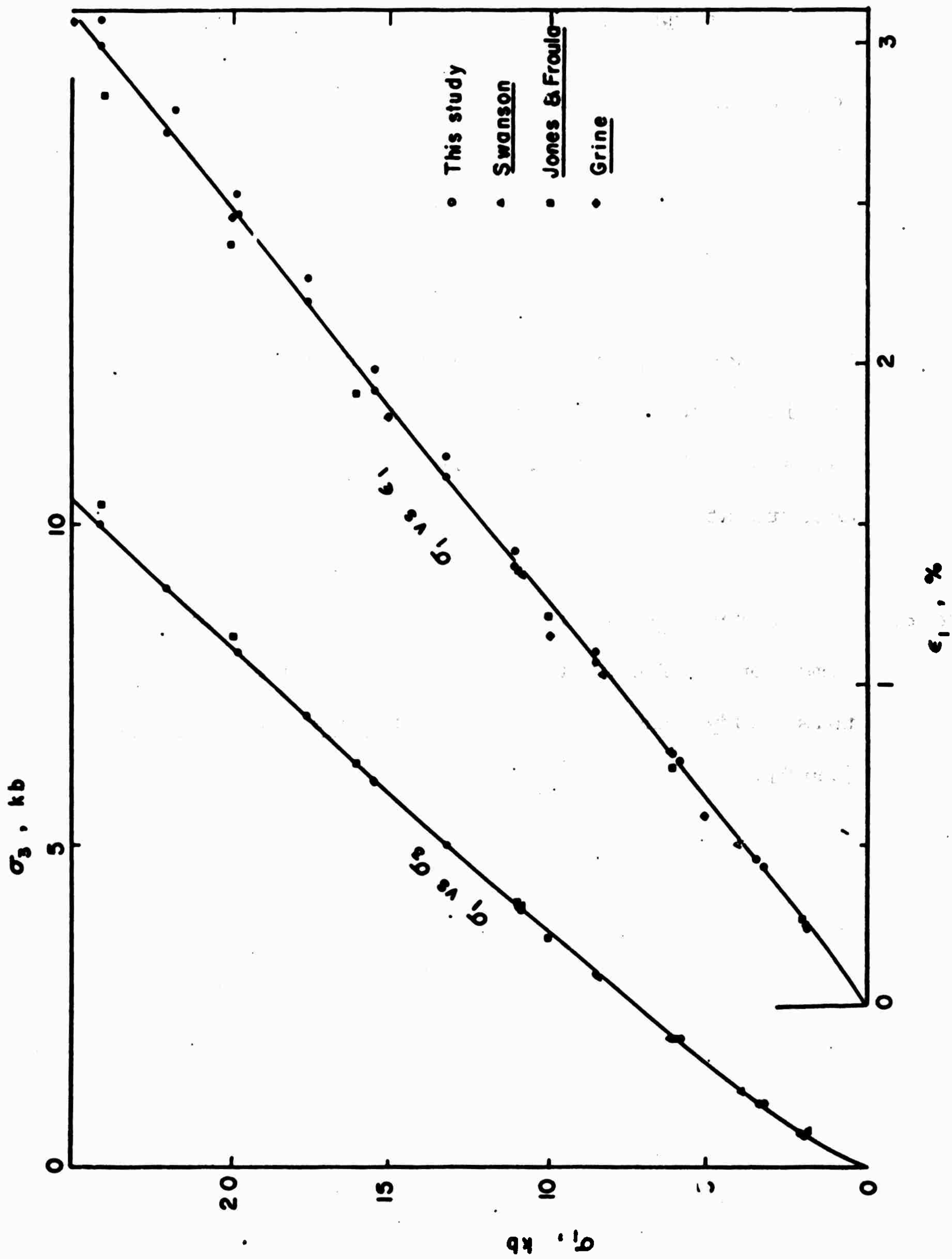

Figure 1 Uniaxial strain behavior of Westerly granite.

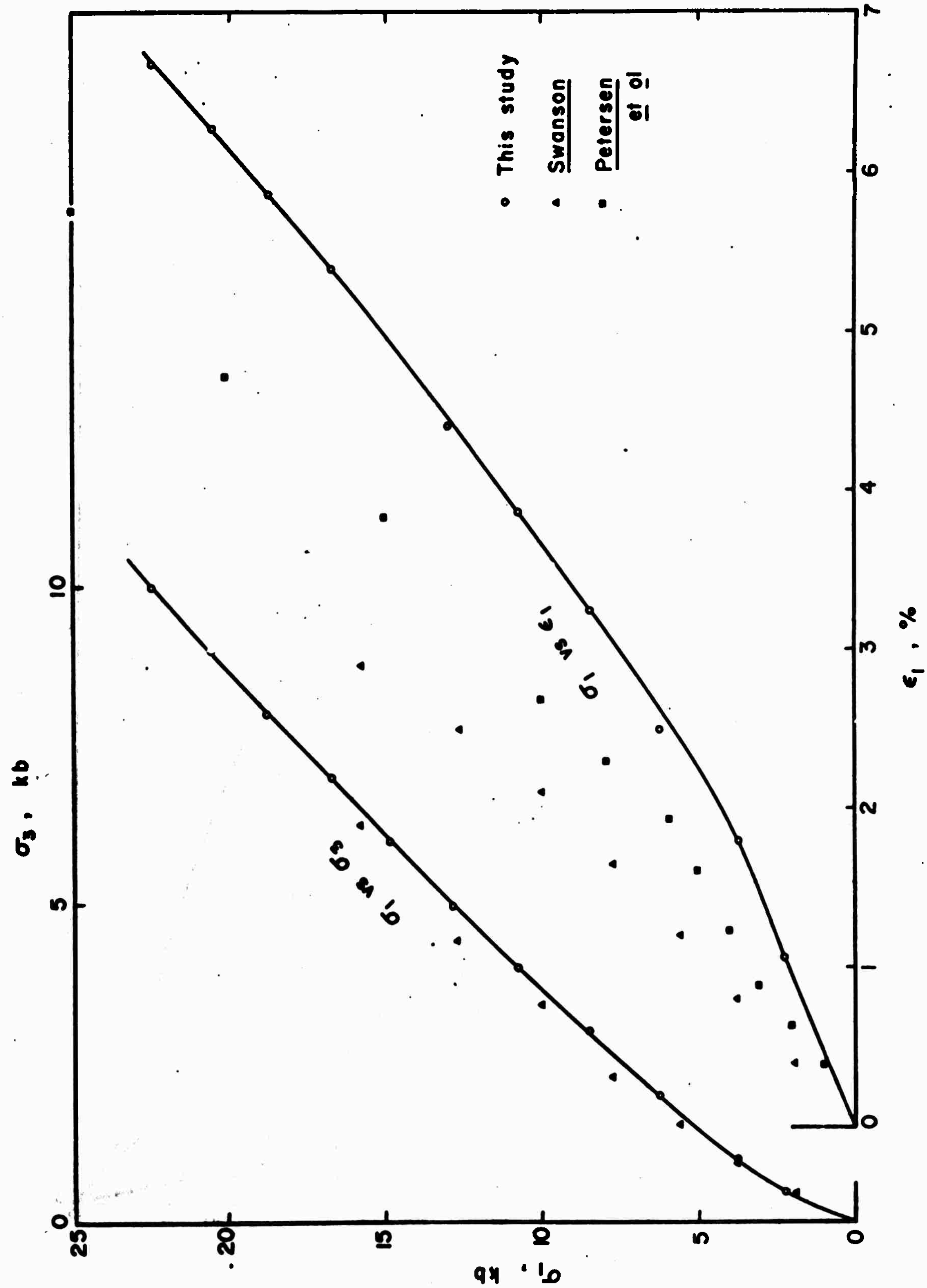

Figure 2 Uniaxial strain behavior for Cedar City tonalite.

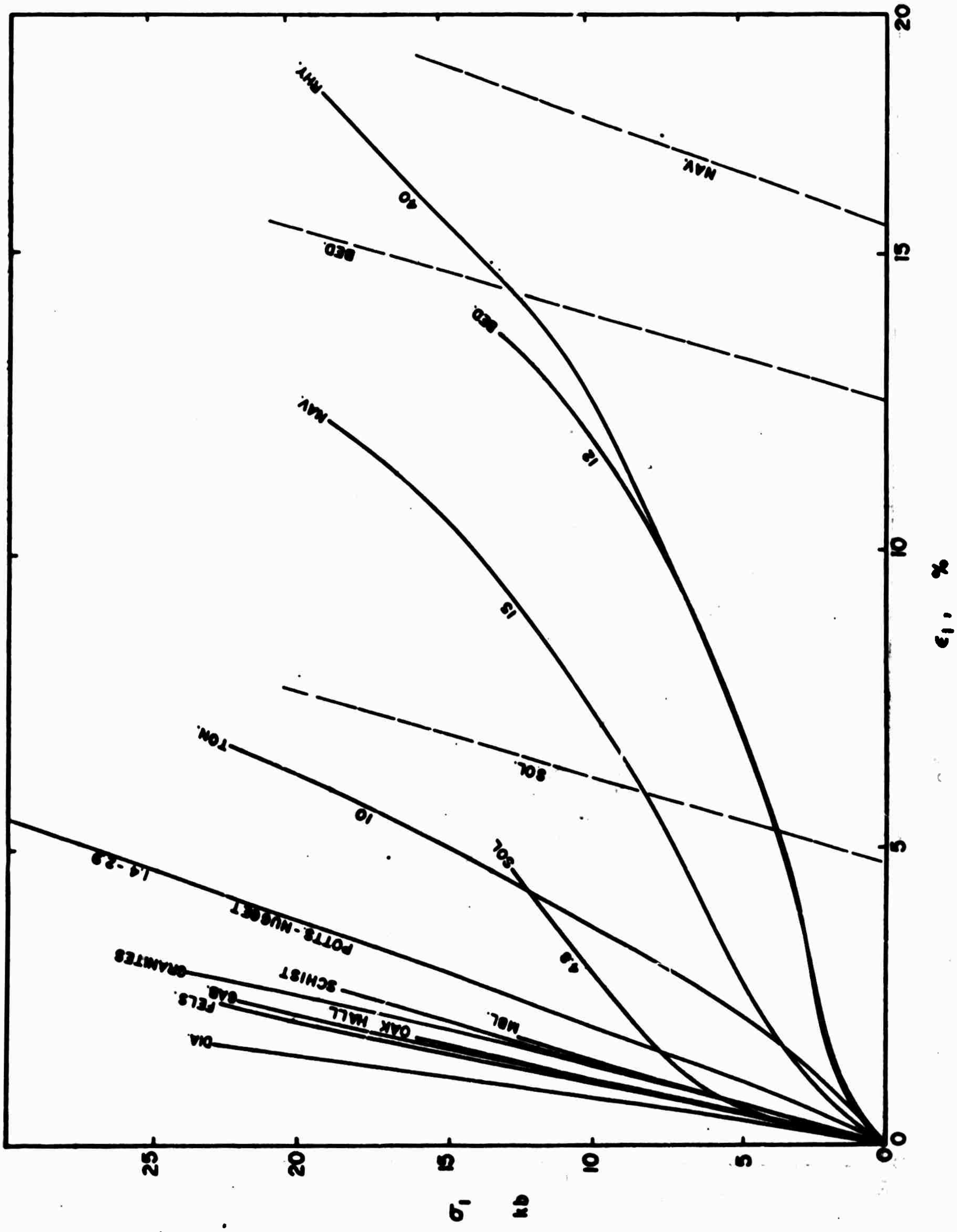

Figure 3 Stress-volumetric strain.

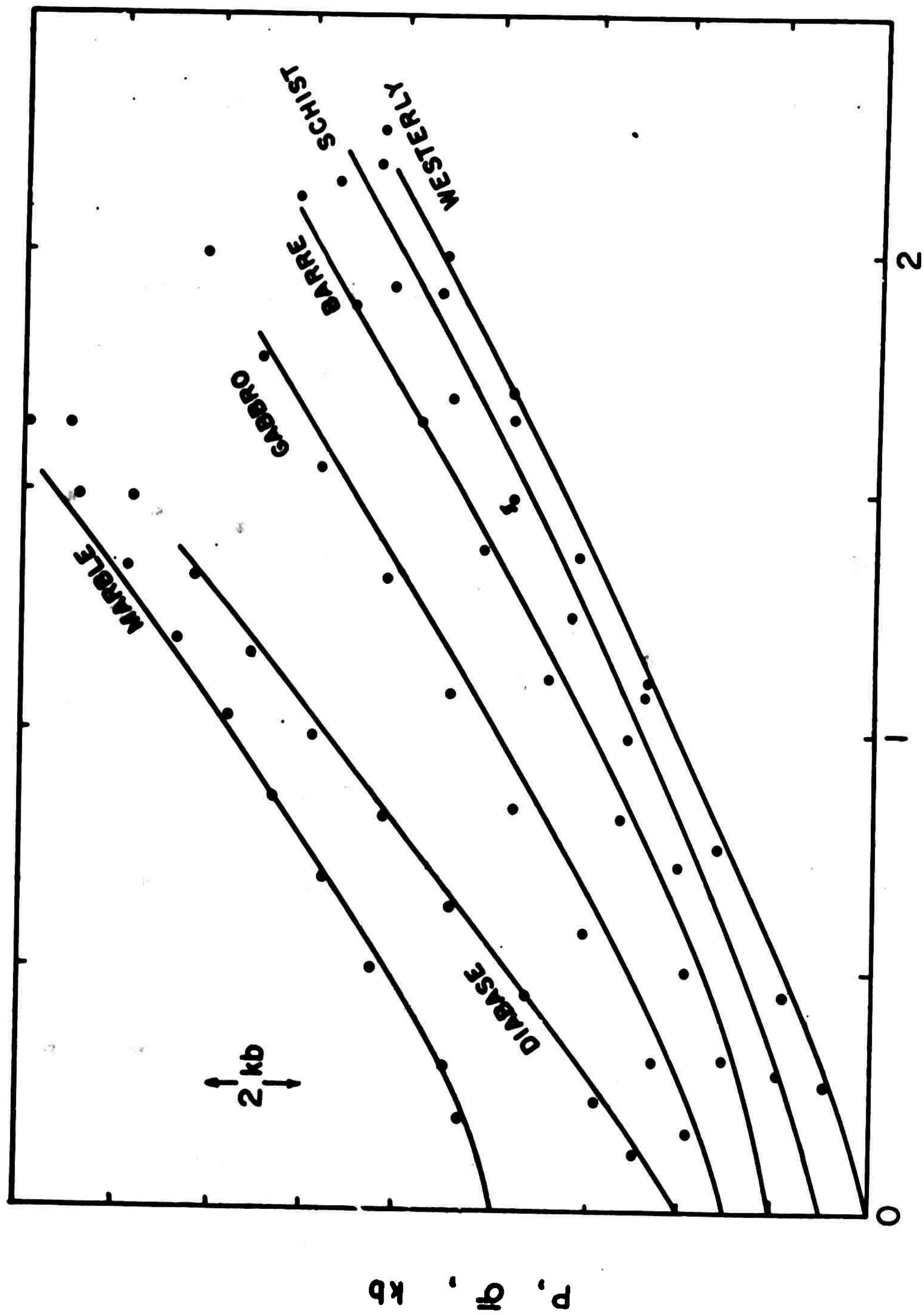

Figure 4 Comparison of uniaxial strain with hydrostatic compression for low porosity rocks.

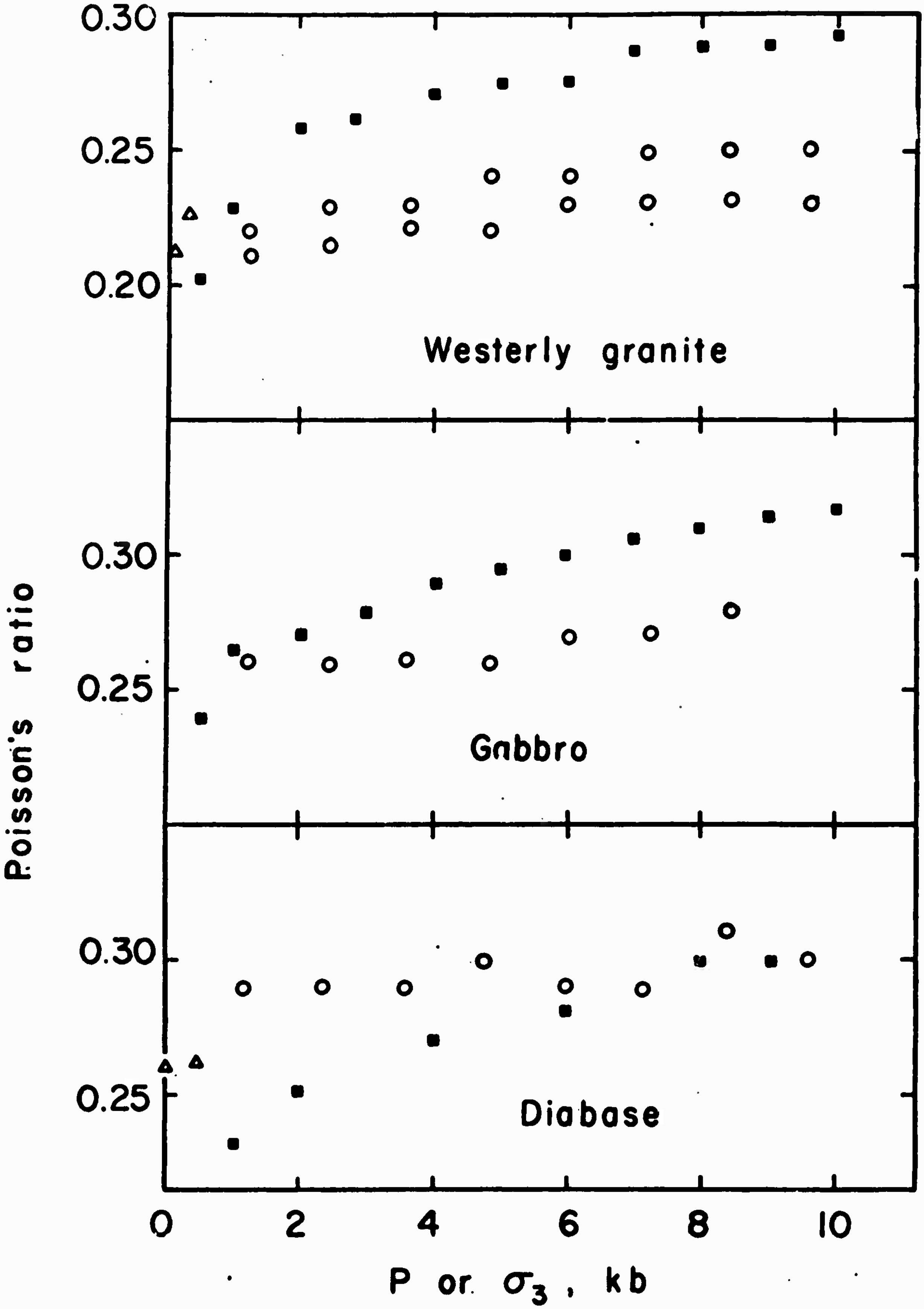

Figure 5 Comparison of Poisson's ratio

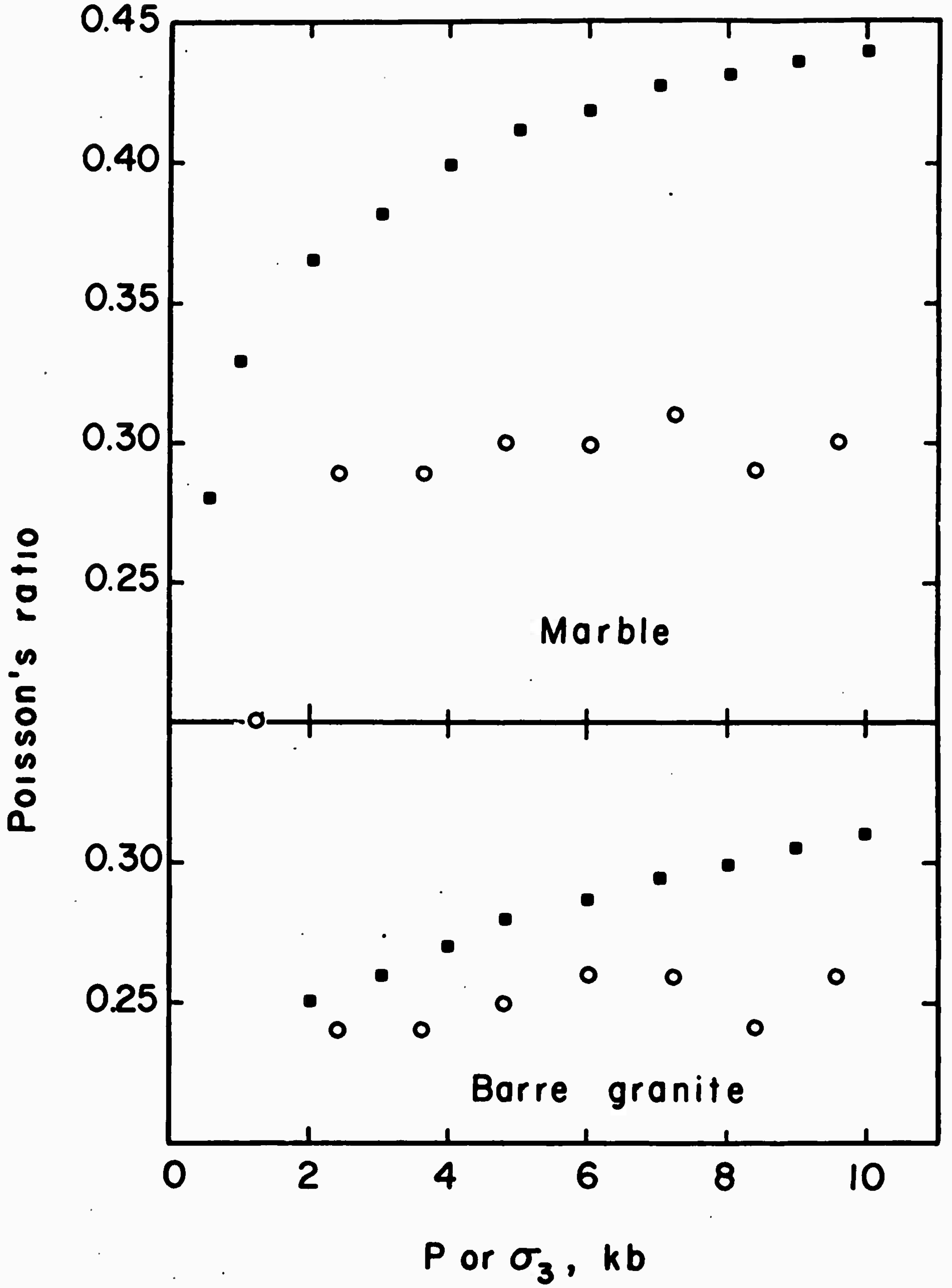

Figure 6. Comparison of Poisson's ratio for uniaxial strain loading with the value measured directly.

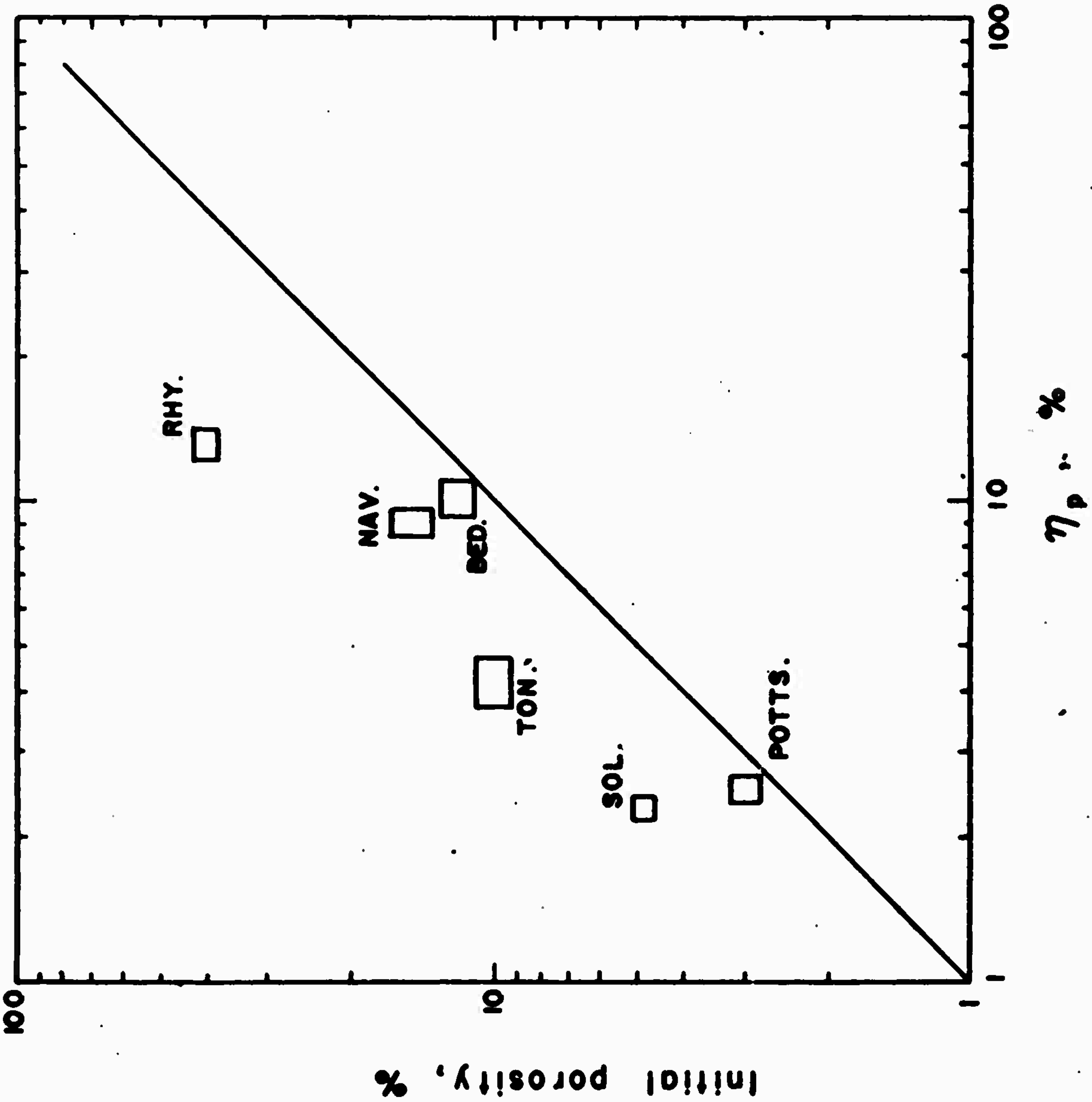

Figure 7. Comparison of permanent volumetric compaction with initial porosity for high porosity rocks.

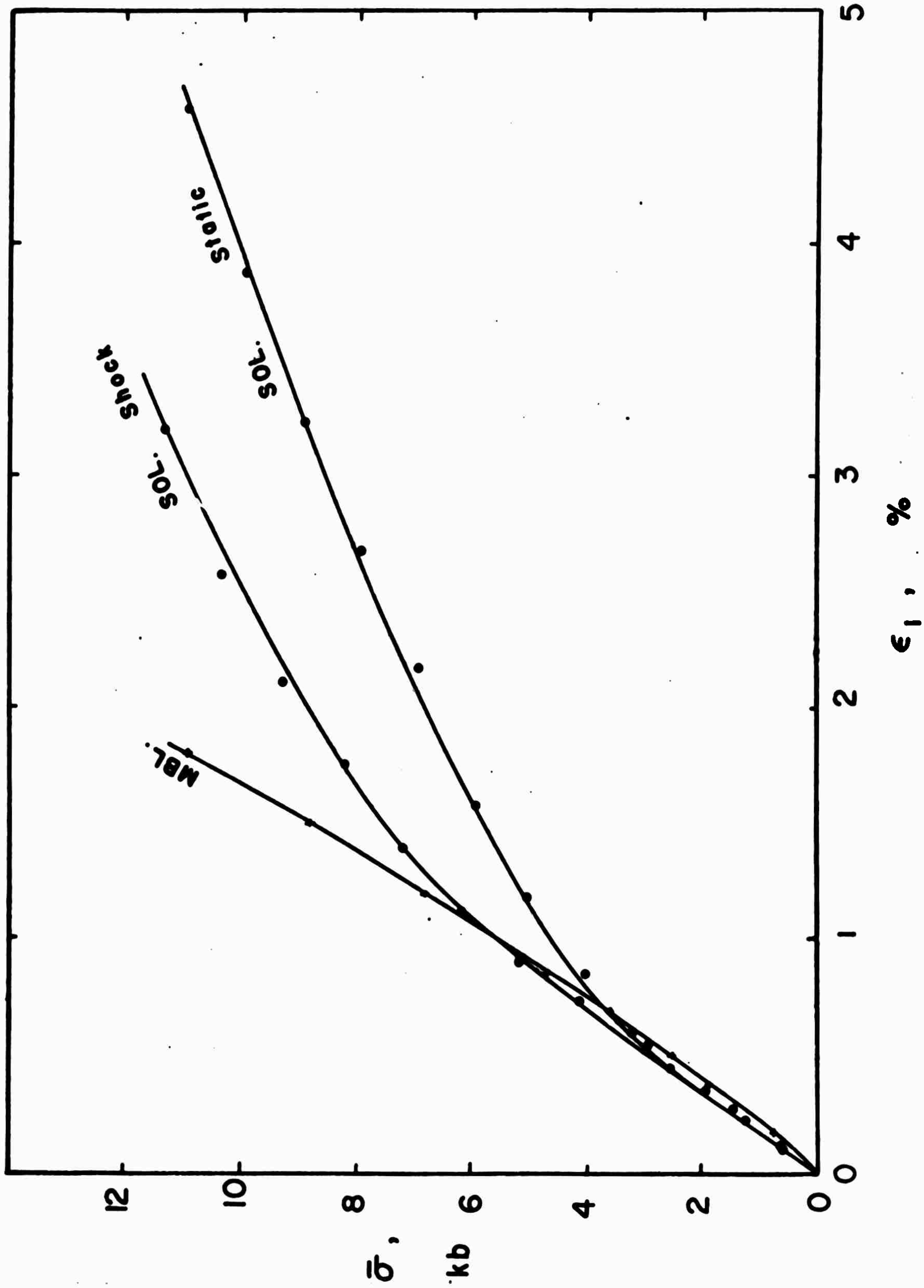

Figure 8. Mean stress vs strain for marble and Solenhofen limestone.

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13. ABSTRACT

Samples of 15 rocks with porosity ranging from nearly zero to 40 percent were deformed in uniaxial strain to stresses which reached 31 kb The principal stress ratio and the volumetric strain were recorded for comparison with experiments done statically elsewhere and with results from shock loading.

The stress-strain relations of low porosity rocks such as Westerly granite are nearly identical with those reported for shock loading. For material with porosity greater than about 2 percent, permanent compaction occurred at the stresses imposed here. Compaction was apparently time-dependent, for nearly twice as much compaction was observed in our static experiments as in shock loading. Macroscopic faulting was not observed.

For rocks of low porosity the stress-strain relation in uniaxial strain loading is closely predictable from compressibility, suggesting that behavior of these rocks was elastic, or, at least, recoverable even to high stress levels. However, Poisson's ratio given by the stress ratio in unaxial loading exceeds that directly measured statically by an appreciable amount, particularly for calcite marble.

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